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DIELECTRIC GASES: REDUCTION OF LEAKAGE COSTS IN HIGH POWER MICROWAVE SYSTEMS

Vincent C. Vannicola
Leon L. Stevens

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Techniques Branch
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FOREWORD

The authors wish to express their gratitude to Mr. Alexander V. Ross, Rome Air Development Center, for his valuable assistance in building and rendering operable the test facility and all its specialized circuitry from which these investigations were performed.

Key Words: Microwaves; High Power; Insulation; Dielectric Gases.

ABSTRACT

Studies and experimental investigations at Rome Air Development Center have established the technical basis for reducing the enormous costs encountered with the leakage of sulfur hexafluoride from high power microwave systems. It was found that sulfur hexafluoride could be diluted with nitrogen or air without undergoing proportionate degradations in peak power handling capability. At slightly higher gauge pressures, such diluted mixtures could be used without reducing peak power handling capability. Procedures for mixing sulfur hexafluoride and other dielectric gases with nitrogen, air, and oxygen are given if maximum efficiency and safety are to be expected. Practical application of the results can reduce leakage costs by 50 to 70 percent. Various examples are given. The adaptation of this technique to high power microwave systems is recommended where leakage of sulfur hexafluoride is a significant cost consideration.

PUBLICATION REVIEW

This report has been reviewed and is approved.

Approved:

ARTHUR J. FROHLICH
Chief, Techniques Branch
Surveillance & Control Division

Approved:

THOMAS S. BOND, JR.
Colonel, USAF
Surveillance & Control Division

FOR THE COMMANDER,

IRVING J. GABELMAN
Chief, Advanced Studies Group

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1. INTRODUCTION

At Rome Air Development Center an investigation has been underway to evaluate the use of dielectric gases in high power microwave systems. Experimental measurements were made to determine the breakdown strength (or increased holdoff microwave power) of a number of dielectric gases including mixtures of these gases with nitrogen, oxygen, and air. Similar measurements at 60 cycles AC are reported in the literature but a thorough literature survey has not turned up any data involving these mixtures at microwave frequencies. The dielectric gases which are under evaluation include sulfur hexafluoride (SF_6), perfluoropropane (C_3F_8), octofluorocyclobutane (C_4F_8 cyclic), perfluorobutane (C_4F_{10}), Freon 114 ($CClF_2$—$CClF_2$), Freon 115 ($CClF_2$—CF_3), and Freon 116 (CF_3—CF_3) of which all are commercial grades.

2. LABORATORY SETUP AND PROCEDURE

Breakdown strength of various gas samples was measured across a 1.34-inch diameter hemisphere located in WR-284 waveguide. A driving frequency of 2856 mc ± 1 mc was used. The large r-f electric field used to break down the gas was produced by a standing-wave resonator. Measurements, nondestruc-

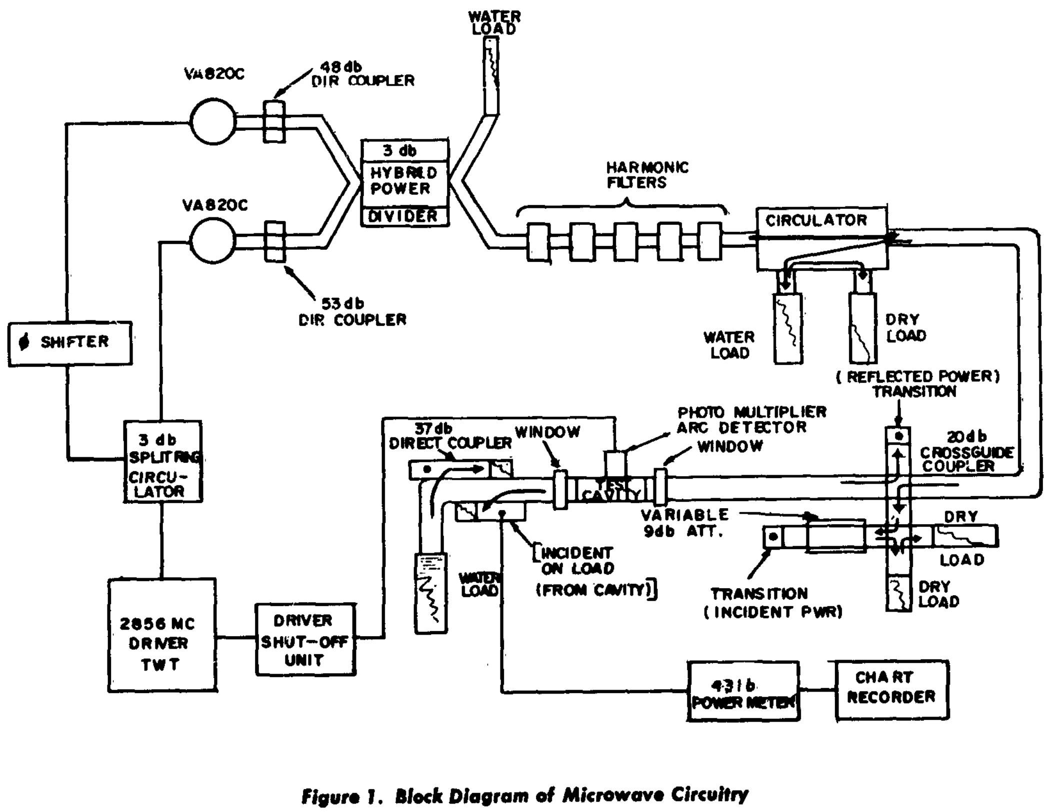

Figure 1. Block Diagram of Microwave Circuitry

tive to the spark gap as well as the gas sample, were obtained by sensing arc onset with a photomultiplier tube and utilizing the output to deactivate the high power microwave source. Breakdown points were plotted with a recorder and power meter assembly. A block diagram and photograph of the microwave circuitry are shown in Figures 1 and 2.

The waveguide resonant structure in which the gas samples were broken down consisted of two inductive irises and a 1.34-inch diameter hemisphere. (Figure 3.) Through the use of ordinary transmission line equations, it can be shown that the r-f electric field E at the hemisphere is approximately $E = 30E_0$ where E_0 is the r-f electric field incident on the cavity. The cavity Q was approximately 400. A photograph of the resonant cavity and associated equipment is shown in Figure 4.

Statistical time lag for arc onset was reduced well below pulsewidth through the use of a radioactive metal plating (3 millicuries Polonium 210) on the surface of the hemisphere. Mixtures of the gases were produced with partial pressure techniques. Prior to the application of each gas sample, the spark gap was evacuated down to about 50 microns Hg. The gaseous equipment is shown in Figures 5 and 6.

The power ratio of SF_6 (normalized to air or nitrogen), *i.e.*, the ratio of the holdoff power of SF_6 to that of air (or nitrogen), was measured at around 16 which is a representative value for S-band.

3. EXPERIMENTAL RESULTS AND OBSERVATIONS

Figures 7, 8, and 9 show the holdoff power versus percentage of SF_6 in mixture with nitrogen, air, and oxygen respectively. Holdoff power is normalized to

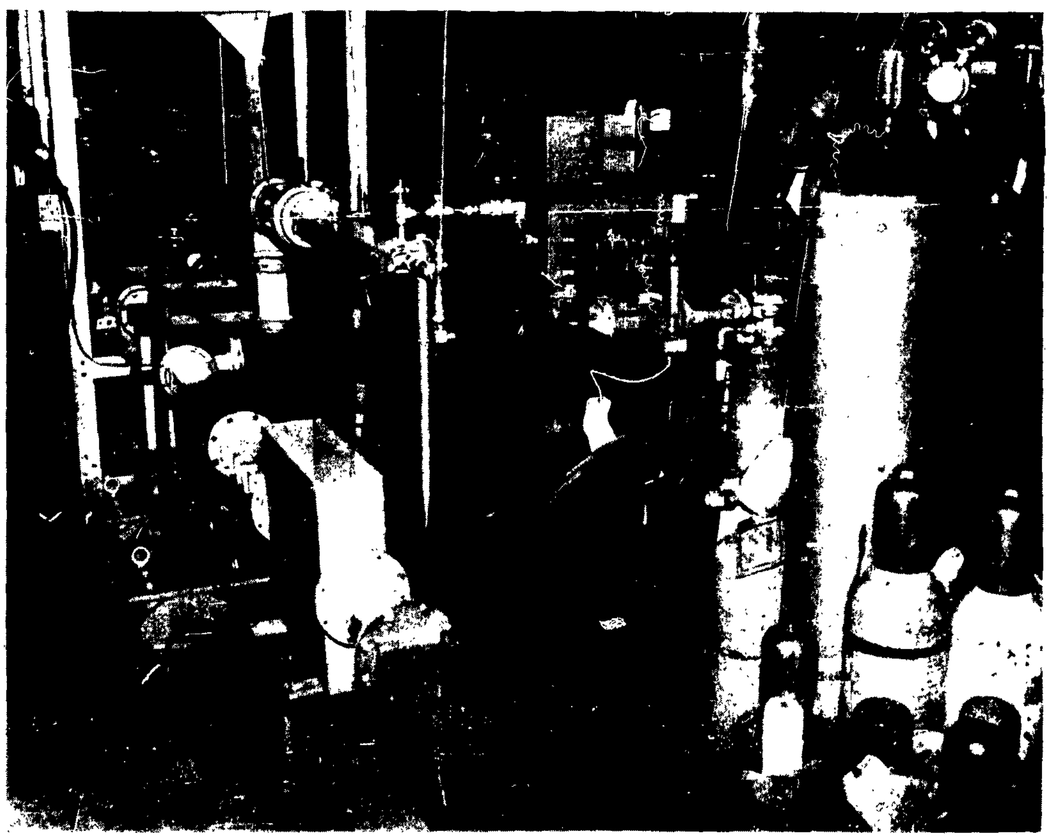

Figure 2. Photograph of Microwave Circuitry

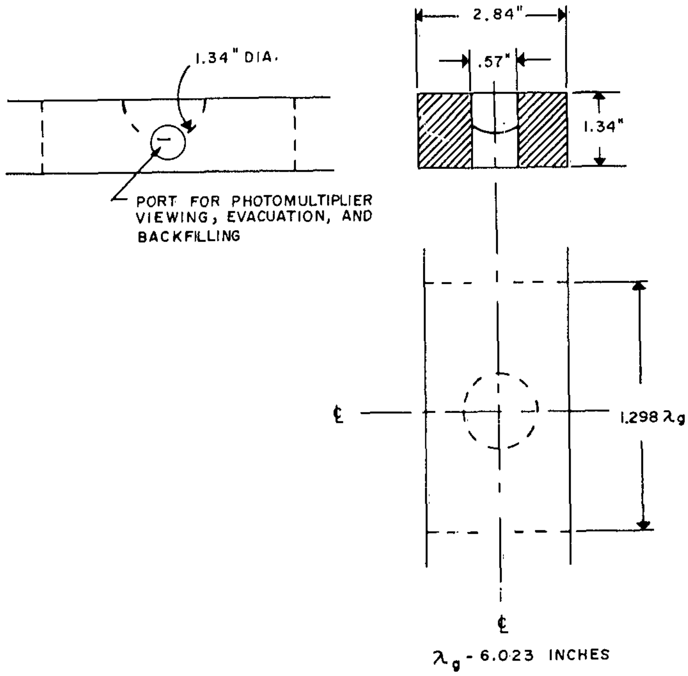

Figure 3. Spark Gap and Resonant Cavity Used for Breaking Down Gas Samples

Figure 4. Photograph of Spark Gap, Resonant Cavity, and Associated Equipment

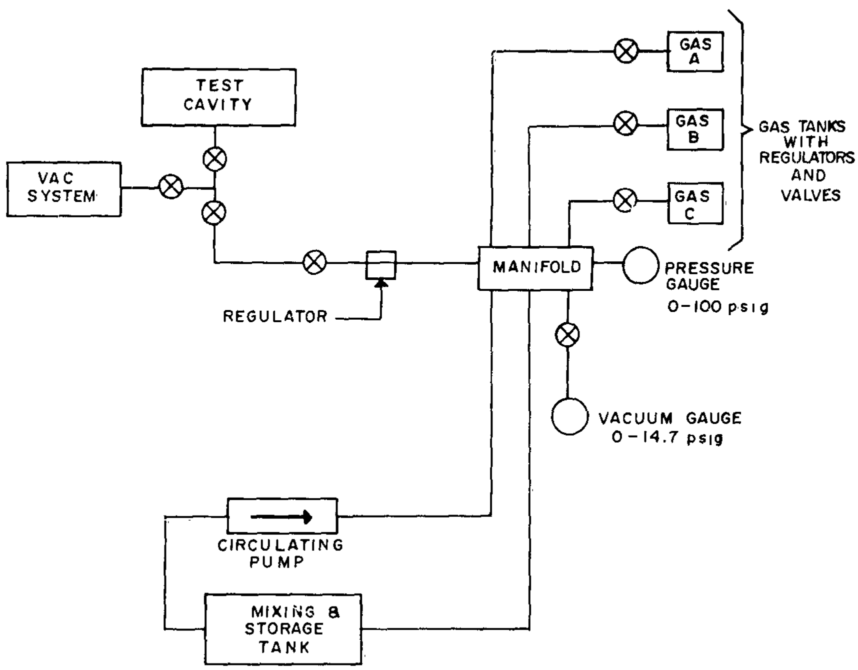

Figure 5. Block Diagram of Gaseous Equipment

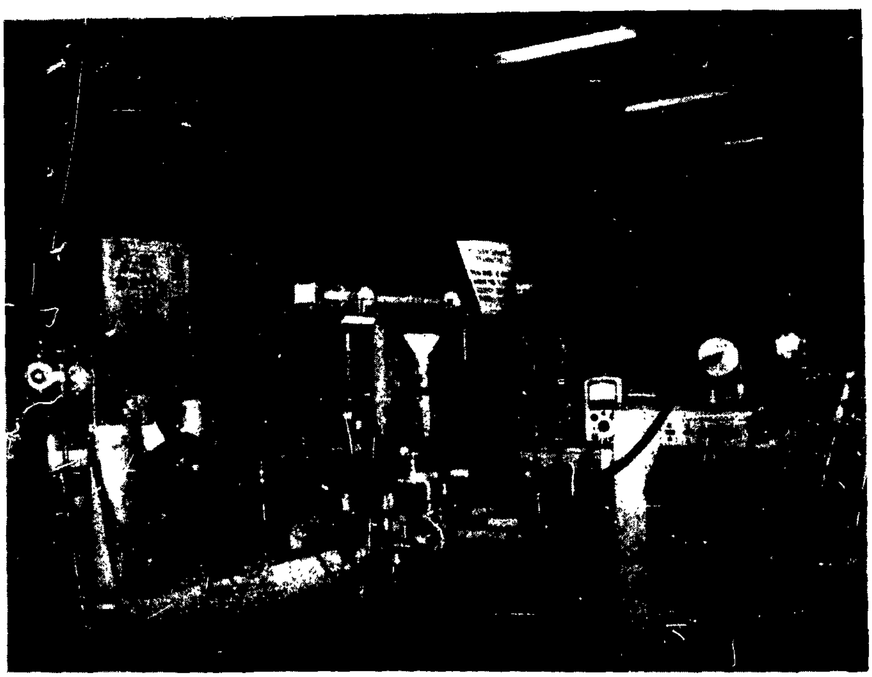

Figure 6. Photograph of Gaseous Equipment

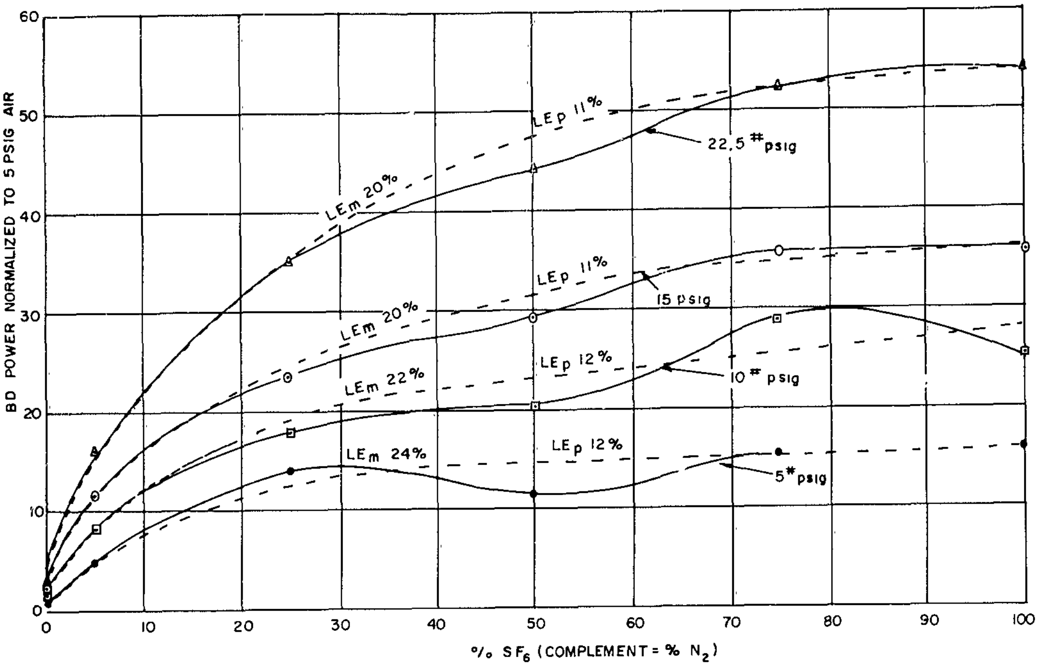

Figure 7. Breakdown Power for Mixtures of SF_6 and N_2 Normalized to 5 Pounds of Air

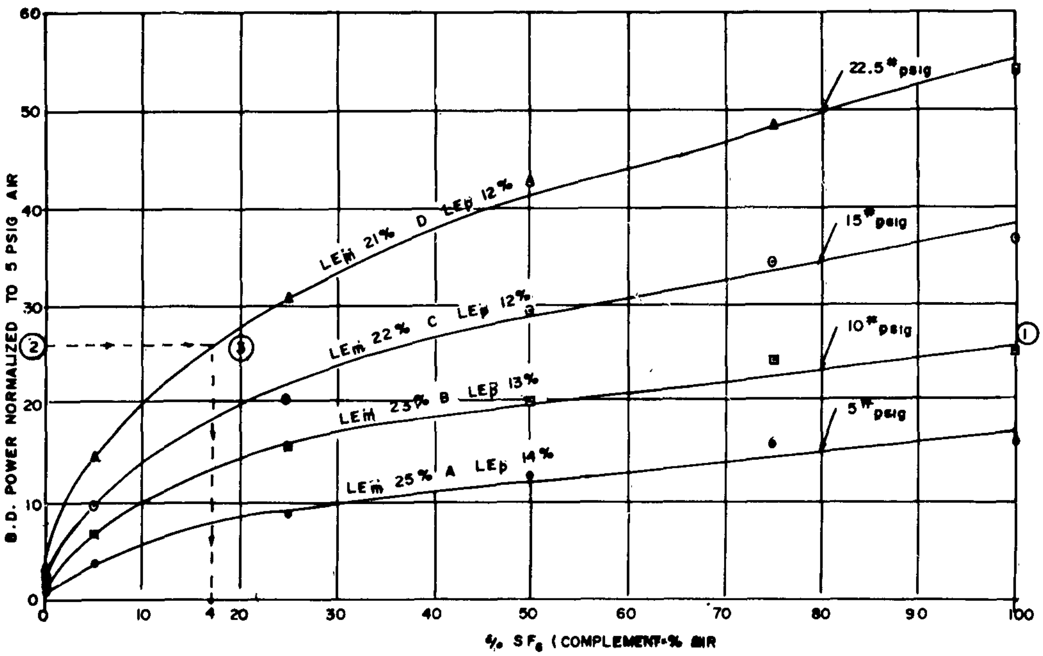

Figure 8. Breakdown Power for Mixtures of SF_6 and Air Normalized to 5 Pounds of Air

5 psig of air as measured across the waveguide spark gap. The family of curves represent 5, 10, 15, and 22.5 psig pressure as indicated.

Measurements of holdoff power were most significant when SF_6 was mixed with nitrogen or air (Figures 7 and 8). A 50/50 percent mixture of SF_6 and nitrogen (Figure 7) yielded about 85 percent of the increase obtainable from displacing air (or N_2) with 100 percent SF_6 (commercial grade). A 25/75 percent (25 percent SF_6—75 percent N_2) mixture gave about 70 percent of the increase obtainable from 100 percent SF_6, and a 5/95 mixture gave about 35 percent of the increase. These results seem to indicate that the dilution of SF_6 with 50 percent (or less) nitrogen has little or no effect on the insulating characteristics of commercial grade SF_6. Greater percentages of nitrogen continue to be relatively harmless to the electron attachment mechanism of SF_6.

Mixtures of SF_6 and O_2 (oxygen) provided another interesting result regarding holdoff power in waveguide. Small quantities of O_2 mixed with SF_6 resulted in a rather sharp decrease in the holdoff power. As the oxygen content exceeded 5 percent, the holdoff power remained fairly constant until the mixture became 50/50. Figure 9 illustrates the dependence of holdoff power on percentage of oxygen content. This set of data serves to indicate that small quantities of oxygen degrade the effectiveness of SF_6.*

4. MIXING PROCEDURES

When mixing a lighter gas such as oxygen or nitrogen with sulfur hexafluoride it was necessary to

*An investigation is now underway to determine the insulating properties of SF_6 under conditions of controlled high purity. The holdoff power of such a sample may render two orders of magnitude improvement over that of the present commercial grade.

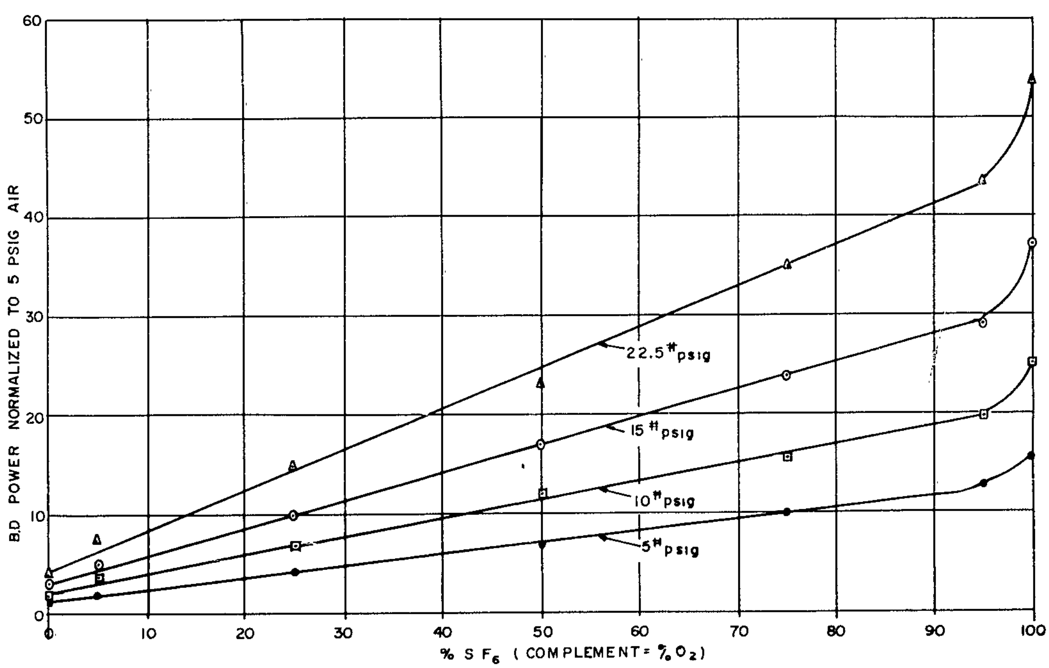

Figure 9. Breakdown Power for Mixtures of SF_6 and O_2 Normalized to 5 Pounds of Air

circulate the gases together in a confined volume to assure a homogeneous batch. Mere valving of the various gases into a confined volume does not necessarily result in a thorough mixture. Observations of this condition were made when a number of samples from the same batch of assumed mixture exhibited different insulating characteristics. The breakdown strength for any individual sample taken from the batch of the assumed mixture was consistent with repeated measurements of only that sample. After a waiting period of several hours the samples showed a marked improvement in uniformity, suggesting that diffusion processes had aided in mixing the gases. Very good consistency between samples was noted after the assumed mixture was circulated with the forced flow produced by a blower located in a closed loop of the confined volume. The procedures described above produced repeatable results.

5. APPLICATIONS FOR REDUCING LEAKAGE COST IN MICROWAVE SYSTEMS

In this experiment, the advantages of using a mixture of SF_6 and a less expensive gas as a dielectric for waveguide pressurization was evaluated. Since all practical systems contain leaks, it is economically desirable to find a mixture which will conserve the more costly SF_6. Let us assume that for moderately low pressures the leak rate is directly proportional to the gauge pressure. One is now faced with conflicting factors: If the percentage of SF_6 is reduced, the mixture is less costly, but the breakdown strength is also reduced, so that one must compensate by increasing the pressure slightly. The increased pressure results in an increase in leak rate.

Thus it is economically desirable to decrease the percentage of SF_6 and increase pressure if

$$\frac{\text{cost of mixture}}{\text{cost of } SF_6} < \frac{\text{gauge pressure required for } SF_6}{\text{gauge pressure required for mixture}}$$

or

$$\text{cost for leakage of mixture} < \text{cost for leakage of } SF_6$$

The three common gases used to dilute concentrated SF_6 were Air, N_2 and O_2. Air is most readily available and would probably be the gas used for mixing in a practical situation. Mixtures of N_2 and SF_6 did show a higher holdoff strength than air and SF_6 but its added cost in remote areas may offset this advantage. Oxygen on the other hand, was least desirable, so its use is not recommended as a mixing agent.

It was found that for all practical mixtures of Air and SF_6 (5 percent SF_6 to 100 percent SF_6), leakage costs decreased with an attendant decrease in the percentage of SF_6 at a pressure appropriate for sustaining holdoff power. Thus the highest practical operating pressure determines what mixture could be used.

Data in Figures 7, 8, and 9 can be used very readily. All three figures show holdoff power versus percentage of SF_6, with pressure as an extra parameter. Holdoff (breakdown) strength is normalized to 5 psig air at STP. The diluting agents for Figures 7, 8, and 9 are respectively nitrogen, air, and oxygen. Mixtures of SF_6 and oxygen as shown in Figure 9 are included for completeness although their use is not economically advantageous.

An example of the usefulness of Figure 8 is given. Suppose a system pressurized with SF_6 at 10 psig has a leakage rate costing $100,000 per year. The microwave system has components which are limited to 22.5 psig, so this is the highest pressure which can be used. It is seen from Figure 8, point ①, that for 10 psig 100 percent will hold off about 26 normalized units, and this is what must be held off in this particular system. Now locate the required holdoff (BD power) on the vertical scale (*i.e.,* 26 at point ②, and traverse horizontally until the desired pressure curve (curve D 22.5 psig in this case at point ③ is determined. Point ③ corresponds to 18 percent SF_6. Thus the mixture is 18 percent SF_6, 82 percent air. The effective loss of SF_6 would be

$$\frac{22.5}{10} \times 18 \text{ percent} = 40 \text{ percent}$$

of the original loss. Since the cost of air can be considered negligible, a saving of about $60,000 out of $100,000 will be realized.

For another example, assume a high power microwave system is required to operate at 30 pounds gauge of sulfur hexafluoride in order to maintain a certain level of power handling capability. If this same system can withstand a mere increase of 2 pounds internal pressure a mixture of sulfur hexafluoride and nitrogen (or air) 50/50 at 32 pounds gauge will sustain peak power holdoff. However, the cost due to leakage will be reduced by about 46 percent. (Interpolated from Figure 7.)

The probable limit of error (LE_p) and maximum limit of error (LE_m) are given on each graph. They were computed by standard methods using a number of arbitrary data points from each curve and the instrumental limit of error of all vital equipment. This information must be taken into account when designing for an actual system.

6. CONCLUSIONS AND RECOMMENDATIONS

The results obtained with mixtures of sulfur hexafluoride and nitrogen are very encouraging and the application of such is highly recommended as a method for reducing the cost of operating high power surveillance systems where it is necessary to pressurize with sulfur hexafluoride.

A note of caution must be taken in regard to mixing. From the results obtained in this investigation it is apparent that mixtures consisting of these heavy molecular weight dielectric gases and less heavy gases such as nitrogen and air must be thoroughly blended prior to backfilling into the microwave system. Failure to perform this task may result in stratified layers of varying mixture percentages in the high power microwave system of which power handling capability will be limited by the weakest strata.

A small percentage of oxygen added to SF_6 appears to degrade power handling capability considerably.

An explosive mixture is obtained when Freon C318 (octofluorocyclobutane, C_4F_8) or Genetron 905 (perfluorobutane C_4F_{10}) is mixed with oxygen. (See Appendix.)

APPENDIX

FLAMMABILITY PRECAUTIONS FOR FLUOROCARBONS

All the gases under investigation are listed by their manufacturers as nonexplosive and nonflammable. There has been no history of these gases being otherwise. In view of the test results cited in the following paragraphs mixing of these gases with oxygen should be reconsidered insofar as their explosive and flammable properties are concerned.

A mixture of Freon C318 (Octofluorocyclobutane C_4F_8) and Oxygen (50/50) at 22 psig underwent an explosive reaction when an r-f breakdown arc was produced within the volume of the confined mixture. The force produced by the blast resulted in broken waveguide windows, a cracked water load, and distorted WR-284 waveguide and associated components. The gas mixture was confined within a high Q brass waveguide cavity (35 cubic inches) containing a small polonium surface, two Varian 1106 windows at each end, and soft solder joints. At the time of arc onset an intense S-band electromagnetic field was present. Prior to filling the cavity with the mixture other gases and mixtures including Freon C318 (100 percent), Oxygen (100 percent), Sulfur Hexafluoride and Oxygen (50/50 percent) were subjected to the same breakdown tests without resulting in an explosive reaction. Any doubt that the explosion was caused by the oxidation of combustible deposits on the inner surfaces can therefore be eliminated.

The possibility that ozone or intense electromagnetic waves was directly or indirectly involved in the reaction was further investigated. A chamber to contain the gas at 22 psig was constructed. A filament

Figure 10. Chamber in Which Flammability of Gases Was Demonstrated

and a spark plug gap with exterior electrical terminals were both built into the chamber. The chamber was evacuated and then backfilled with a mixture of Freon C318 and Oxygen (50/50 percent). Partial pressures were used to obtain the mixture. It was intended to determine whether a kindling point such as that of a hot filament could initiate the reaction as well as the electric arc. The hot filament did produce an explosion of Freon C318 and Oxygen (50/50 percent mixture) at a total pressure of 22 psig. Figure 10 illustrates the degree of distortion which was produced by the explosion. The plates on both ends of the pipe are one eighth inch brass. Prior to the explosion the longitudinal axis of the valve and the filament connectors (shown on the top plate) were parallel. A rich deposit of carbon black was found throughout the inner surface of the chamber indicating that a more intense reaction would have resulted if the mixture had been richer in oxygen.

These results serve to issue a word of caution as to the flammability of Freon C318. Although Freon C318 is an excellent dielectric gas and appears to be non-flammable and non-explosive in the presence of air (the manufacturer so states) it appears to be violently explosive (with the possibility of toxic by-products) when mixed with oxygen. The Freon C318 used for testing was taken from two bottles which may or may not have contained contaminants. Those contemplating the dilution of Freon C318 with oxygen (a less expensive electron attaching gas) should be made aware of the results of this experiment.

Flammability tests were extended to the other fluorocarbon gases recommended for electrical insulation. The only other gas which underwent a similar but less intense reaction was Genetron 905 (perfluorobutane—C_4F_{10}).